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Beyond Scalability: The Impact of Critical Mineral Scarcity on the Cost-Optimal Design of the European Energy Transition

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Extended Abstract

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Abstract Summary

Achieving climate neutrality requires a rapid transition toward high shares of renewables, yet energy system optimization models typically assume the unconstrained scalability of technologies. In an increasingly fragmented geopolitical landscape, the restricted availability of critical materials threatens energy security and transition pathways. This study utilizes PyPSA-Eur to investigate how limited supplies of copper, lithium, nickel, cobalt, and graphite reshape the optimal design of a renewable-dominated European power system.

By imposing global constraints on minerals rather than technologies, we capture system-wide trade-offs and competition for scarce inputs. Results demonstrate that resource scarcity induces fundamental structural reorganization rather than mere cost increases. As constraints tighten, the system undergoes a pronounced substitution effect: reliance on short-duration battery storage declines, displaced by expanded long-duration hydrogen systems and transmission capacity. Transmission infrastructure emerges as a consistently robust flexibility option, shifting the system from localized temporal balancing toward long-term spatial smoothing.

A central analytical contribution is the extraction of shadow prices, which quantify the marginal system value of scarce minerals. These prices escalate nonlinearly, signaling a transition from a flexible to a genuinely constrained regime where the system is forced into less efficient alternatives and higher curtailment. Our findings highlight that flexibility is a portfolio property; when one pathway is restricted, the system reallocates investment across complementary alternatives. This research underscores the need for coordinated infrastructure development and supply diversification to ensure a resilient European energy transition.